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Spectrum Visualization and Measurement of Power Parameters of Microwave Wide-Band Noise

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***Abstract*—A method for an adequate visualization of a microwave intense noise spectrum envelope in a wide frequency range (several octaves), measurement of its power parameters, and detection of a narrow-band signal with unknown frequency and power against the noise background is presented. This method is based on an application of a nonheterodyne principle of microwave frequency (and power) conversion using a gyromagnetic converter, which operates in two regimes in turn: the resonance detection and the cross-multiplication. A block scheme and an operation of a two-channel measuring device combining the mentioned functions are discussed.**

***Index Terms*—Cross-multiplication, gyromagnetic converter, microwave wide-band noise, power parameters, resonance detection, spectrum power density.**

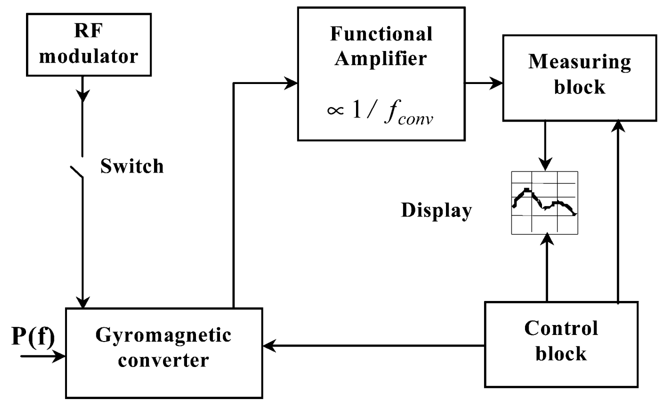

Fig. 1. Block-scheme of the measurer of spectrum power density.

I. Introduction

An adequate visualization of wide-band microwave spectra (up to several octaves), as well as measurement of their parameters, is an actual problem in the design, testing, and practical application of microwave active devices, such as oscillators, amplifiers, active mixers, etc., especially those of high and middle power levels [1].

The method and the device for its realization presented herein combine several functions. The first one is the reproduction and visualization of a wide-band random signal (in this paper it will be referred as "noise") spectrum envelope. The second function is the measurement of the wide-band noise spectrum power parameters, such as spectral power density, integral power in the chosen frequency range, spectrum bandwidth, and its central frequency. The third function is the detection, identification, and measurement of narrow-band deterministic signals that might be present in the spectrum of a random signal. Detection and identification of a narrow-band deterministic signal at the background of a wide-band random signal is necessary when developing and exploiting microwave noise generators. There is a class of microwave wide-band noise generators, where the main source is a narrow-band monochromatic signal, and the output random signal is formed by means of applying of a wideband modulation. The presence of deterministic components in the noise spectrum influences the quality of the random signal, that is, how white the generated noise is. Another practical problem is multisignal wide-band radar analysis, when it is necessary to obtain adequate information on both deterministic and random signals present in the microwave path. It is important to differentiate actual signal spectra components from those parasitics that might appear due to nonlinear effects in the measuring devices, as well as to detect low-intensity deterministic components in the background of random spectra.

Standard spectrum analyzers for microwave frequencies usually use heterodyne principle of frequency conversion. To identify numerous channels of reception, expensive high-quality microwave preselectors, complicated calibration techniques, and cumbersome computer processing are required. The difficulties increase when a source of radiation is unmatched with the input of an analyzer, or when radiation from several sources must be analyzed simultaneously. Problems occur also using broadband power meters with a set of parallel filters at the input, because of the necessity of matching them with the radiation sources over all of the broad frequency range. Besides, the dynamic range of microwave detectors is limited, and this does not allow, for example, measuring noise spectrum power parameters in the presence of an intense interference.

The *measurer of spectrum power density* (MSPD), the block-scheme of which is shown in Fig. 1, was developed at Moscow Power Engineering Institute (Technical University) [2], [3], and it is free from the shortcomings mentioned above. This device has found application for microwave power spectrum measurements over a wide frequency range (more than two octaves) and allows for frequency-selective panoramic (i.e., with envelope spectrum view) measurements based on gyromagnetic converters (GCs). As shown in Fig. 2, the GC is a section of a transmission line (usually coaxial or stripline) containing a high-Q

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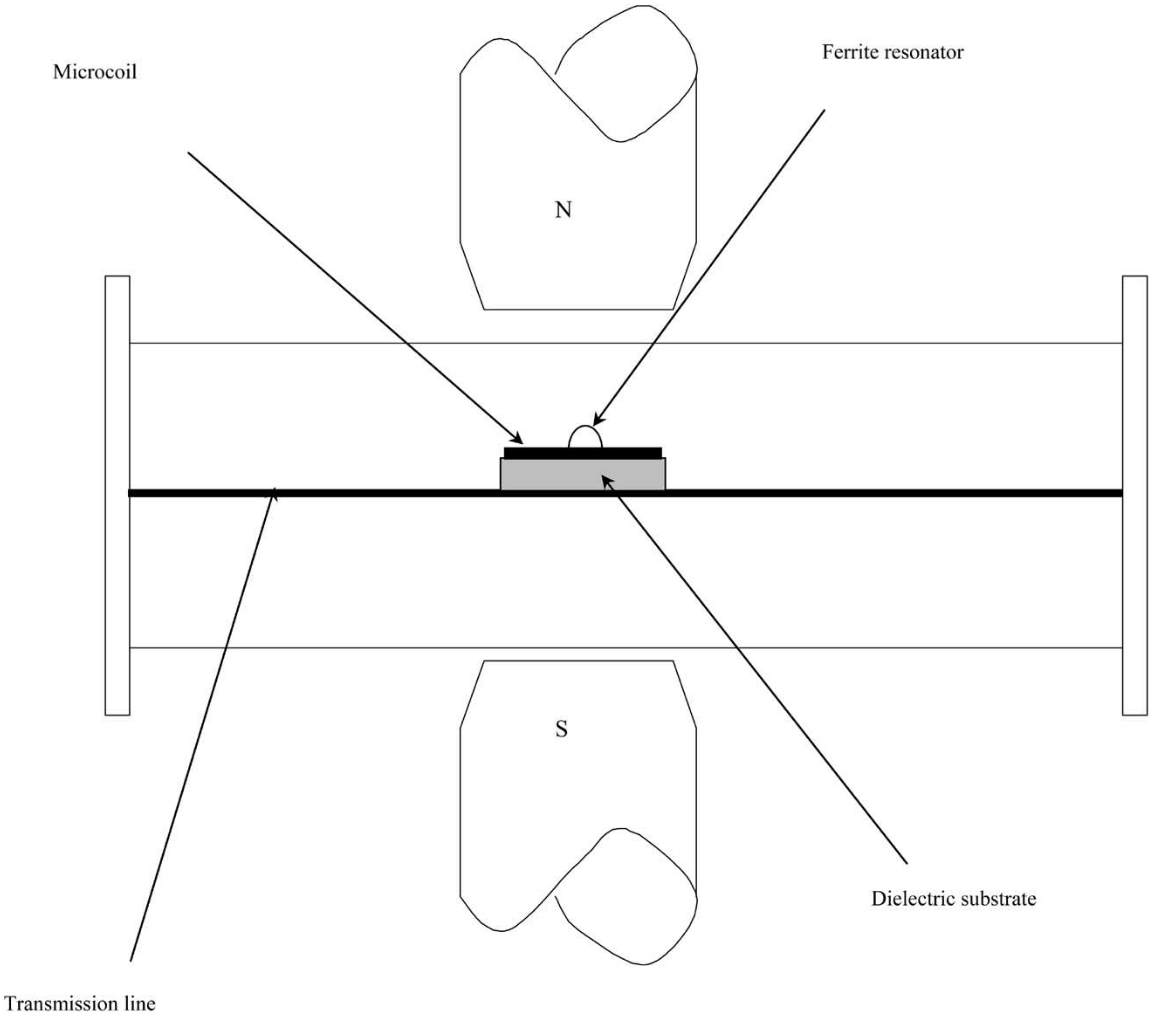

Fig. 2. Schematic of a gyromagnetic converter.

monocrystalline ferrite resonator on a dielectric base. The ferrite resonator is surrounded in its equatorial plane by a microcoil, which is a planar spiral coil of about 15–25 turns made of a wire having a diameter of several dozens micrometers (typically, 40–60 μm). This microcoil is used for both a radio-frequency (RF) modulation of the ferrite resonance frequency and getting an induced voltage due to an interaction of the ferrite resonator with a microwave magnetic field. The transmission line is placed into a bias magnetic field for the ferrite saturation and its resonance frequency variation in the scanning range of the spectrum analysis. The bias electromagnet contains a specific coil to tune the bias field of the ferrite according to the saw-tooth law. The principle of the GC operation is based on stable nonlinear resonance effects (SNLREs) at ferromagnetic resonance (FMR), when microwave power is lower than spin-wave instability level [1], [4]. There are two possible regimes of the GC operation. First is the resonance detection (RD), when there is no RF modulation of the ferrite resonance frequency, and the second is the cross-multiplication (CM), when the resonance frequency is modulated by an RF oscillation [1], [2]. The typical operating frequency range of the MSPD starts from 300 MHz, if monocrystalline garnet ferrites with low saturation magnetization are used. The upper frequency of the YIG ferrite device belongs to the 8-mm frequency range (up to 40 GHz); however, depending on the design of the GC and the type of the ferrite used (for example, monocrystalline hexagonal ferrite), the frequency range can be up to 100 GHz [4]. The GC passband Δf_{GC}, which determines the MSPD frequency resolution, is usually on the order of megahertz. The intrinsic linear dynamic range of a GC is determined by the linearity of the GC conversion coefficient versus incident power, and typically is about 25–30 dB [2], [4]. The dynamic range of the GC is limited by a power level, at which there is saturation due to the spin-wave instability excited in the ferrite resonator. Typically, the measured minimum spectrum power density when using the YIG ferrite spherical resonator over the 3-cm waveband is $5{\cdot}10^{-11}$ W/Hz, and maximum is more than $5{\cdot}10^{-5}$ W/Hz. Experimentally, various constructions of ferrogarnet GC on different types of microwave transmission lines in decimeter and centimeter frequency band operate at continuous power from 10^{-3} to 10^{3} W. To broaden the dynamic range of the MSPD operation, additional attenuators at the input of the GC are used. Due to the frequency selectivity of the GC and the nonheterodyne frequency conversion with the constant conversion coefficient over a broad frequency range, the MSPD allows measuring high-intensity noise power density in the given frequency band, central frequency of the spectrum, and integral noise power [3]. It is important that the device exhibits stability at microwave power overload of about 10–15 dB above the linear dynamic range. This means that at the nonlinear regime the ferrite heats up, the FMR deteriorates, and the ferrite stops absorbing microwave energy, cools down, and the GC restores its working capability.

These devices are especially useful, for example, for testing microwave signal amplification by wide-band microwave output power tubes, at multifrequency regimes in the microwave transmission line path, and for measuring rather small useful signal spectrum density in the presence of intense electromagnetic interference. The demands on the preselectors at the input (-60 dB loss outside the passband and minimum possible loss in the passband) may be less stringent when using the GC, because the latter has a selectivity curve equivalent to that of the four-resonator high-Q ferrite filter [3], [4].

The MSPD operates as follows. When measurements are conducted, the GC is used at the resonance detection regime (without the RF modulation). The RF modulation in the GC of the MSPD is used only for calibration purposes of the device, and after the calibration is accomplished, it is switched off. Part of the spectrum of a microwave wide-band random (noise) signal falls into the FR resonance line and causes both precession and nutation of the ferrite magnetization vector, so that there is a variation of the longitudinal component of the magnetization vector M_z.

The behavior of the magnetization vector of the FR is described by the equation of motion with a dissipative term in one of the forms, for example, the modified Bloch's form [5]

$$\frac{d\vec{M}}{dt} = -\mu_0\gamma[\vec{M}\times\vec{H}] + \frac{\omega_r}{\mu_0}\left(\chi_0\vec{H} - \mu_0\vec{M}\right) \tag{1}$$

where $\vec{H}$ is a total effective magnetic field acting on the magnetic moment $\vec{M}$ of the FR; $\mu_0 = 4\pi\cdot 10^{-7}$ H/m is permeability of vacuum; $\gamma = 1.76\cdot 10^{11}$ C/kg is a gyromagnetic ratio; χ_0 is the static magnetic susceptibility; and ω_r is the relaxation frequency. Assuming that the ferrite is magnetized by the magnetic field H_{0z} along the z-axis, and the microwave magnetic field has only transversal $h_{x,y}$ components, at the small angles of the magnetization vector precession, the longitudinal component M_z is related to the transversal microwave components of magnetization vector m_x and m_y by a square-law equation [5]

$$M_z(t) = M_0 - \frac{1}{2M_0}\left(m_x^2(t) + m_y^2(t)\right) \tag{2}$$

where M_0 is the equilibrium magnetization amplitude, which coincides with the saturation magnetization M_S for ferrites with low internal field of magnetic crystallographic anisotropy, e.g., ferrogarnets. The transversal components of magnetization vector are found from the FR external magnetic susceptibility tensor equation in frequency domain [5]

$$\vec{m}(\omega) = \overset{\leftrightarrow ext}{\chi_m}(\omega)\cdot\vec{h}(\omega) \tag{3}$$

where $\vec{h}(\omega) = h_x(\omega)\vec{x}^0 + h_y(\omega)\vec{y}^0$ is the transversal microwave magnetic field, and $\omega = 2\pi f$.

The resulting magnetic flux variation due to variation of the longitudinal component of magnetization vector induces a voltage in the microcoil

$$V(t) = k\frac{dM_z}{dt} \tag{4}$$

where the coefficient k depends on the geometry and the parameters of microcoil wire. The spectrum of the voltage (4) in the microcoil is

$$|V(\omega_{\text{conv}})| = \omega_{\text{conv}}kF(\omega_{\text{conv}}) \tag{5}$$

where $F(\omega_{\text{conv}})$ is the spectrum of the longitudinal component M_z at the frequencies of the converted signal $\omega_{\text{conv}} = 2\pi f_{\text{conv}}$.

The converted spectrum (5) is then processed by a wide-band functional amplifier (see Fig. 1) with special amplitude-frequency characteristic $|K(f_{\text{conv}})| = K_0/f_{\text{conv}}$ to provide proportionality of the input spectrum power density at every frequency to the converted signal spectrum for adequate reproduction of the spectrum envelope.

Sometimes narrow-band deterministic signals are present at the background of a wide-band random (or "noise") signal. For a number of electromagnetic interference/compatibility applications, it is important to tell these signals from the noise spectrum envelope inhomogeneities, which are of a random origin, and also identify their intensity and frequency. However, the MSPD cannot do this.

II. Proposed Measuring Method and Device for its Realization

A method presented herein allows combining both measurement of the noise spectrum power parameters and detecting narrow-band deterministic signals against the noise background. The principle of this is based on physical phenomena at the interaction of a ferrite resonator with microwave electromagnetic field, that is, redistribution of the converted spectrum, when the RF modulation of the ferrite resonance frequency is switched on and off. A two-channel measuring device for the realization of this method broadens the possibilities of the MSPD [7]. The block-scheme of the two-channel measuring device (TCMD) is presented in Fig. 3.

In this device, the regime of the GC operation is periodically switched from the resonance detection to cross-multiplication, and the spectrum envelopes obtained in two regimes are compared. The presence of modulation in cross-multiplication regime "underlines" the deterministic signal components if they are present at the background of the wide-band random noise signal [7]. This is due to the signal and noise redistribution in the spectrum of the converted signal when modulation is introduced. At the cross-multiplication regime, the total magnetization field contains a "constant" component H_{0z} (which is actually changed with a "saw" law because of the resonance frequency slow tuning in the range of observation), and an RF modulation part

$$H_z = H_{0z} + h_{\text{mod}\,z}\cdot\cos(\Omega t + \varphi). \tag{6}$$

The spectrum of the variation of the longitudinal component of magnetization vector ΔM_z, when the microwave signal with the

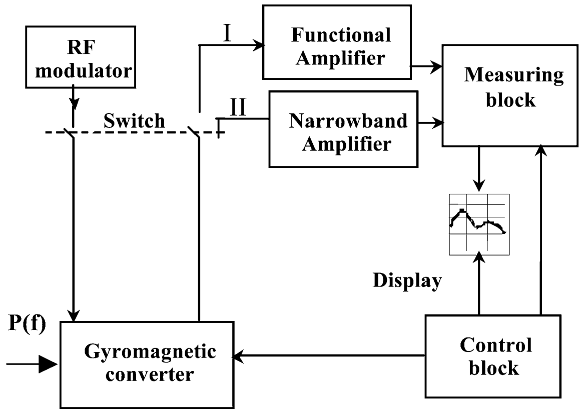

Fig. 3. Block-scheme of the two-channel measuring device.

magnetic field amplitude $h_m(\omega) = \sqrt{h_x^2 + h_y^2}$ acts on the FR, is [8]

$$\Delta M_z = \omega_M^2 h_m^2 \frac{1}{8M_S\delta^2} \times \left(\Psi_0(a,p,q) + \sum_{n=1}^{\infty} \Psi_n(a,p,q)\cos(n\Omega t - \varphi_n)\right) \tag{7}$$

where M_S is the saturation magnetization; δ is half of the FR resonance line width at the level of -3 dB; and $\omega_M = \mu_0\gamma M_S$. Functions $\Psi_n(a,p,q)$ are the normalized harmonics of the longitudinal component of magnetization, and $\varphi_n = \varphi_n(a,p,q)$ are the corresponding phases of the harmonics [8], [9]. These harmonics depend on the relative detuning of the ferrite resonator

$$a = \frac{\omega - \omega_0}{\delta} \tag{8}$$

the normalized magnetic field amplitude of modulation for the GC

$$q = \frac{\mu_0 \cdot \gamma \cdot h_{\mathrm{mod}z}}{\Omega} \tag{9}$$

and the relative modulation frequency

$$p = \frac{\Omega}{\delta} = \frac{2f_{\mathrm{mod}}}{\Delta f_{\mathrm{GC}}} \tag{10}$$

where $\delta = \pi\Delta f_{\mathrm{GC}}$, $\Omega = 2\pi f_{\mathrm{mod}}$.

Fig. 4 illustrates the physics of interaction of the microwave signal with an FR, when the resonance frequency of the latter is modulated by a signal of frequency f_{mod}. The longitudinal component M_z of the magnetization vector varies in time when the additive sum of a random and deterministic signals act on the ferrite resonator in the vicinity of its resonance frequency, and a voltage is induced in the microcoil.

The power spectral density of the converted noise is found using the correlation theory of normal stationary random processes and Weiner–Khinchine theorem [6]. According to (2), the longitudinal component of magnetization ΔM_z is related to the squares of transversal components $m_{x,y}(t)$, which are normal random processes with dispersion $\sigma_{x,y}^2$, respectively, if the microwave noise $h(t)$ is a normal random stationary process. If an

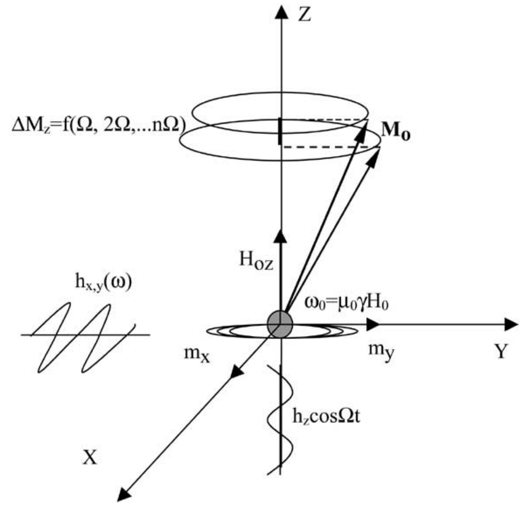

Fig. 4. Interaction of microwave signal with the ferrite resonator at modulation of its resonance frequency.

additive sum of a noise and a deterministic microwave signal (signal + noise) acts on the GC operating in the RG regime, then there are two terms in the converted energy spectrum, due to "noise" and "signal and noise" beatings, and these parts of the spectrum are both continuous [10]

$$F_{RD}(\omega_{\mathrm{conv}}) = F_N(\omega_{\mathrm{conv}}) + F_{SN}(\omega_{\mathrm{conv}}) \tag{11}$$

$$F_N(\omega_{\mathrm{conv}}) = \frac{2\delta k^2(\sigma_x^2 + \sigma_y^2)}{M_0^2} \cdot \frac{\omega_{\mathrm{conv}}^2}{(2\delta)^2 + \omega_{\mathrm{conv}}^2} \tag{12}$$

$$F_{SN}(\Omega) = \frac{\delta k^2(\sigma_x^2 + \sigma y^2)}{M_0^2} \cdot P(\omega) \cdot \left(\frac{\omega_M}{2\delta}\right)^2 \frac{\omega_{\mathrm{conv}}^2}{\delta^2 + \omega_{\mathrm{conv}}^2}. \tag{13}$$

At the CM regime, when the modulation is introduced into a spiral microcoil of the GC, the discrete deterministic signal energy spectrum is added

$$F_{\mathrm{CM}}(\omega_{\mathrm{conv}}) = F_N(\omega_{\mathrm{conv}}) + F_{SN}(\omega_{\mathrm{conv}}) + F_S(n\Omega) \tag{14}$$

where $F_S(n\Omega)$ is found from (7). The first two terms in (14) are the same as in (11), since modulation in the microcoil does not affect the variation of the longitudinal component of magnetization vector associated with a random signal or beating "signal and noise." Fig. 5 schematically shows continuous and discrete components of the ΔM_Z spectrum at comparatively low frequencies of the converted signal ω_{conv}. Thus, when the RF modulation at the CM regime is present, the signal-to-noise ratio increases compared to the RD case. As a result, the envelopes of the same converted noise spectrum containing the narrow-band signal at the CM and RD regimes differ, and the typical panoramic view on the display of the MSPD shown in Fig. 6 illustrates this.

The principle of the deterministic signals detection on the background of wideband microwave noise is based on this difference of spectrum envelopes [7]. The corresponding two-channel device for this method implementation shown in Fig. 3 was realized on the basis of the MSPD described in Section I. The first *(Measuring)* channel containing a

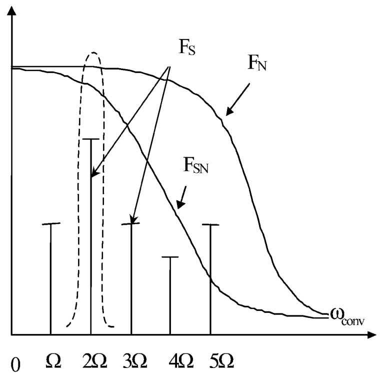

Fig. 5. Components of the spectrum of the converted additive sum "signal" + "noise."

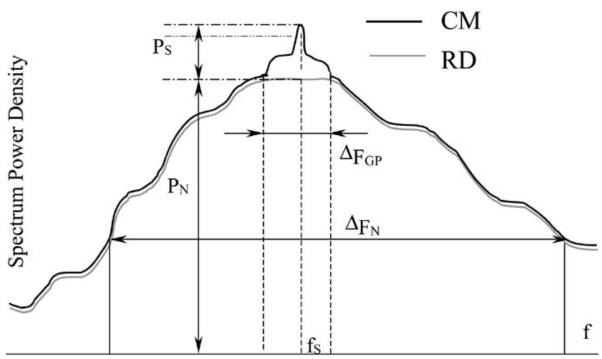

Fig. 6. Panoramic view of a wide-band noise and a narrow-band deterministic signal at the resonance detection and cross-multiplication regimes.

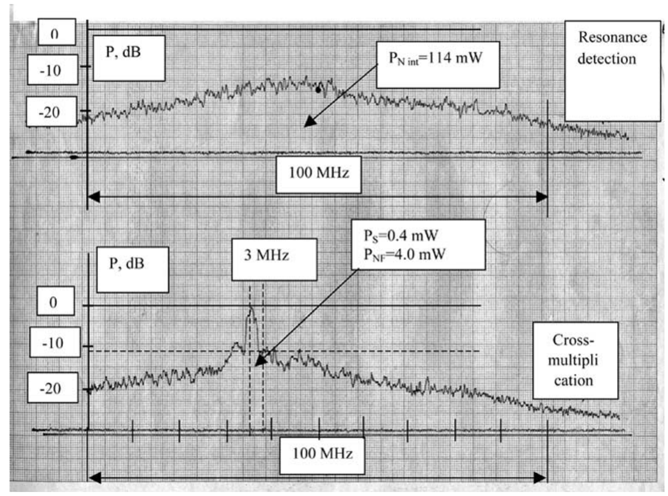

Fig. 7. Plotter record of wide-band noise and signal envelope at the resonance detection and cross-multiplication regimes of the TCMD operation.

wide-band functional amplifier works only when the GC operates in the RD regime. The second *(Detecting)* channel contains a narrow-band amplifier, for example, with central frequency tuned at the second harmonic of the modulation signal frequency. The modulator is an oscillator with high stability of its frequency typically chosen in the range of 1–10 MHz. The low-pass and high-pass filters have corresponding cutoff frequencies to separate the modulation signal in the GC microcoil from the signal at the second harmonic of the modulation frequency.

The experimental two-channel device allowed reliable detection of microwave narrow-band deterministic signals, whose power was up to 30 dB less than an integral power of the background noise signal. The GC of this experimental device was designed using a ferrite spherical resonator having a diameter of 0.5 mm. The resonator was made of monocrystalline YIG ferrite doped with Ca, Bi, and V ions, and had a comparatively low saturation magnetization of $4\pi M_S = 300$ Gauss (or $M_S =$ 23.9 kA/m). The width of the ferrite resonance line at the level of -3 dB was about 2 MHz at frequencies above 300 MHz. The narrow-band block, shown in Fig. 3, was a frequency-selective RF amplifier with a passband of 1 kHz tuned to the second harmonic of the modulation frequency. The frequency and the amplitude of modulation were optimal for getting the maximum voltage induced in the spiral coil of the GC at the second harmonic of modulation frequency. The first-order harmonic cannot be used, because it is necessary to separate the modulation signal in the microcoil from the induced voltage. Since the amplitudes of the harmonics in the converted signal decrease with the order of the harmonics [8], the second harmonic should be used as the most intense one. According to studies of an optimum modulation regime [8], [11], the normalized magnetic field amplitude of modulation for the GC was $q = 3.5$, and the relative modulation frequency was $p =$ 0.8. The plotter output of an additive sum of wide-band noise and signal at the resonance detection and cross-multiplication regimes of the two-channel measuring device operation is presented in Fig. 7. The input signal-to-noise ratio corresponding to this figure was -24.5 dB in the scanning band of 100 MHz. The measured amplitude of the detected signal was 0.4 mW. The spectrum envelope in the vicinity of the detected signal resembles the form of the second derivative of the FR resonance curve, or the form of the second harmonic of the FR magnetization versus detuning, $\Psi_2(a)$. This specific form increases the reliability of the signal distinction from an inhomogeneity in the wide-band random spectrum envelope.

It is important that the microwave narrow-band signal instability does not lead to the necessity of the frequency-selective block passband widening. This is possible due to the nonheterodyne frequency conversion by a GC, since the frequency of a converted deterministic narrow-band signal is independent of the microwave frequency carrier, but is determined only by a harmonic of a stable modulation frequency [2]

$$f_{\rm conv} = n f_{\rm mod}, \quad n = 2, 3, 4 \ldots. \tag{15}$$

The minimum possible passband of the narrow-band amplifier is determined only by the condition of nondistortion of the spectrum envelope at fast frequency sweeping at panoramic observation of the spectrum.

Design of the GC on the basis of prospective high-anisotropy monocrystalline hexagonal ferrites with high Q-factor allows increasing the operation band of the proposed method and device to millimeter-wave frequency range without necessity of using intense external magnetic fields [4].

III. Conclusion

Using stable nonlinear resonance effects in high-quality monocrystalline ferrite resonators at their interaction with microwave random and deterministic signals, it is possible to provide both measurement of power parameters of wide-band intense noise and detection of narrow-band signals at the noise background. Essential increase of signal-to-noise ratio is achieved in the two-channel measuring device that uses gyromagnetic converter, by simultaneous narrow-band amplifier and RF modulation switching on. Due to frequency-selectivity and nonheterodyne principle of frequency conversion, measuring devices that employ gyromagnetic converters have a number of advantages. They are free from parasitic channels of reception associated with heterodyne and intermodulation harmonics, can operate at high power levels, and can be used for visualization and measuring power (spectrum) parameters of radiations produced by high-power microwave devices.

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